Role of Macerals - An Underappreciated Coal Quality Parameter For Unburned Carbon Characterization and Control

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Maceral describes the microscopically recognizable organic constituents of coal. Unlike the minerals with well defined compositions and crystalline structures, macerals vary widely in chemical and physical properties. All have the suffix - inite and are classified into three groups - vitrinite, exinite or liptinite and inertinite. The first two groups are traditionally held to be reactive, inertinite being less reactive. ISO 7404.3, ASTM Standard D 2799 and may other national standards describe the methods of analysis.

Macerals generally occur in association with each other and are known as micro-lithotypes, the names depending on the types and concentration of the different groups. The maceral compositions of coals of different ranks are different. For maceral groups of the same rank, vitrinite contains more oxygen, exinite more hydrogen and inertinite more carbon. The volatile matter content is highest in exinite, lowest in inertinite and that for vitrinite lying in between. Coal with a major concentration of inertinite is therefore likely to have reduced combustibility compared to that containing higher proportion of exinite or vitrinite. If all combustion parameters remain unchanged, the unburned carbon level for such an inertinite rich coal can be expected to be high.

The paper describes some investigations into the role of macerals on coal reactivity and carbon burn out carried out on laboratory drop tube facility, pilot scale boiler and full scale power plants. It also suggests a plan for an international program for developing a maceral based index to predict unburned carbon level during pulverized coal combustion.

The petrographic analysis of macerals is used world-wide to predict properties of carbonization process. The influence of macerals on combustion processes was reported in 1968. Unburnt carbon in ash was found to be largely the result of incompletely burnt inertinite materials on a chain grade stoker and a PC Unit.

Laboratory studies of coal macerals have been carried out world-wide which include Australia, Canada, China, India, South Africa, U.K. and USA. The coals of the USA and UK are mostly of carboniferous origin, enriched in vitrinite and exinite groups. The coals of the southern hemisphere and those of India and China originating from Gondwanaland have the inertinite group as their dominant maceral component. Although the role of macerals on combustion efficiency and unburnt carbon has been reported in the literature over the past twenty years, these information have been hardly recognized by the Power Industry. The maceral composition is not included in specifications for coal trading. This is perhaps because of the relatively cheap price and abundance of coal where a small proportion of unburnt carbon was not of great consequence.

With the advent of the use of Low NO_x Burners, where the chances of complete oxidation of coal is less favorable compared to the previous mode of PC combustion, in uncontrolled burners, the wastage of the heating value with its impact on generation cost has been in prominence. Secondly, coals are being traded world wide where more coals from the southern hemisphere are being exported.

It is therefore surprising, if not disappointing, that the Combustion Engineers and Utilities are yet to take note of these petrological properties.

To cite but a fraction of the published work, a UK project studied twenty coals - eight coals from one US seam & four other US coals, three from Australia, one from the UK, one Colombian, two South African and one from Zimbabwe. These were studied in a drop tube for the effect of rank, maceral composition on the char morphology and reactivity. The results showed that the maceral composition and their association control the char particle size, morphology, char reactivity and burnout characteristics.

In a Canadian Study using a pilot plant boiler, the unburnt carbon and combustion efficiencies were found to be inversely related to the inertinite content of the coal.

A recent US study reported the influence of maceral composition on the size of utility flyash containing greater proportion of unburnt carbon.

The reactive properties of exinite and most forms of vitrinite are acknowledged. The "less reactive" label of the inertinite group has been disputed. Semifusinite, micrinite, macrinite, inertodetrinite, sclerotinite and fusinite, grouped together are labeled as inertinite. Semifusinite has been shown to have equal or greater combustion reactivity than vitrinite.

The problems besetting these studies are the heterogeneity of macerals, difficulty in making concentrates and effort in conducting research under realistic combustion conditions. Semifusinite, often the most abundant maceral within the inertinite group, has a wide diversity ranging in reflectance and morphology, giving rise to formation of different products when subjected to laboratory transformation.

Australia, the world's largest coal exporting country, has many sources with a high inertinite content. A significant amount of research has been carried out by the Australian CSIRO. Their study has shown that all inertinites are not inert in the combustion process. Their relative rates of combustion of the variety of chars from within both the vitrinite and inertinite groups of macerals need to be determined. A Laser Micro Reactor based study has reported the ability to measure the relative combustibility of PC sized maceral particles under true combustion conditions.

In an Indian study, the characterization of unburnt carbon in Power Station flyash showed a strong relationship with the makeup and not the quantity of the inertinite group.

An EPRI/ UK study has proposed an index for the prediction of carbon burnout based on a 3.4 MBtu/h facility, TGA and automative char analysis.

In summary, numerous independent studies world-wide have clearly shown the role of petrographic properties of coal on combustion completion. National/International standards exist for analysis. Emission compliance by in- furnace NO_x control has increased the unburnt carbon level in power generation. Deregulation/privatization of the Utility Industry world- wide have focussed on the need of minimizing generation cost. Despite the heterogeneity of the macerals, the professional community should implement an International Project to develop an indicator to predict the quantity of unburnt carbon from pulverized coal combustion for Power Generation. This should be based on representative coals from both hemispheres, fired in laboratory, pilot scale and Utility units.

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Summary

1. Numerous World-wide Studies Show The Role Of Coal Macerals On Unburned Carbon Level Of Flyash.

2. There Are National & International Standards For Maceral Analysis.

3. Heterogeneity Of Macerals Are Recognized.

4. The Power Industry Has Not Recognized The Usefullness of the Maceral Properties of Coal.

5. In-furnace NO_x Control Increases Unburned Carbon Level in Power Generation.

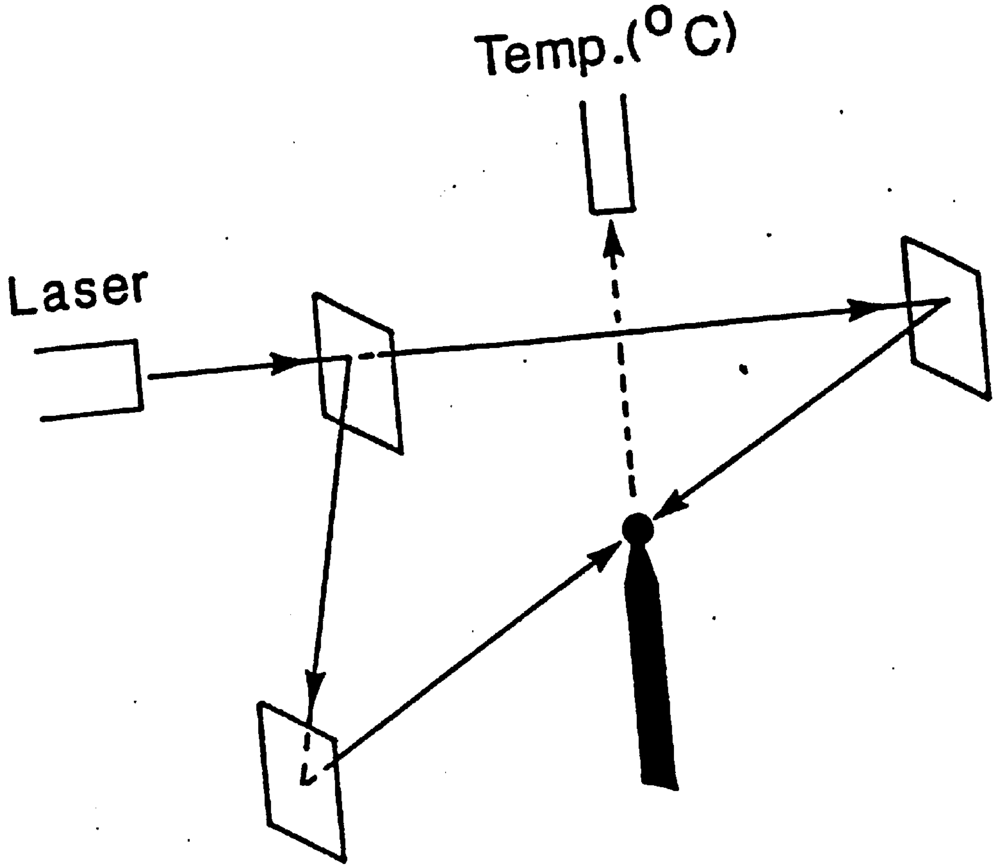
6. Deregulation/Privatization Of The Utility Industry Have Focussed On The Need Of Minimizing Generation Cost.

7. Some Work Is In Progress For Development Of Maceral-based Unburned Carbon Index.

8. An International Project Should Be Undertaken Based On Carboniferous & Gondwanaland Coals.

Inert coal macerals in combustion (Nandi *et al*, CCRL, Canada

	Western Canadian bituminous	Pennsylvania bituminous
Proximate % (dried)		
Volatile matter	24.8	36.3
Fixed carbon	57.0	54.3
Ash	18.2	9.4
Ultimate % (dried)		
Carbon	70.4	75.5
Hydrogen	4.0	5.5
Sulphur	0.3	3.2
Nitrogen	1.1	1.4
Oxygen	6.0	5.0
Ash	18.2	9.4
Macerals %		
Vitrinite	40.6	73.2
Exinite	0.0	11.6
Micrinite	6.4	5.8
Fusinite	35.2	3.4
Semi-fusinite	17.8	6.0
Combustible in fly-ash		
Initial	59.8	16.8
After optimization	41.9	<15.0



Schematic of the laser microreactor method.

BITUMINOUS COAL CHARACTERISATION

Analysis	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Proximate (wt% composition - moisture free)																				
Volatile matter	43.5	38.8	24.3	23.4	22.6	16.7	19.2	17.1	22.6	25.5	25.1	27.4	22.5	27.7	30.6	29.6	34.4	20.7	18.4	23.9
Fixed Carbon	52.1	54.5	60.5	65.6	71.5	71.5	75.4	74.8	74.4	72.8	70.5	69.5	67.8	63.7	51.6	55.6	56.0	40.1	50.4	50.7
Ash	4.4	6.7	15.2	11.0	5.9	11.8	5.4	8.1	3.0	2.6	4.4	3.1	9.7	8.6	17.8	14.8	9.6	39.2	31.2	25.4
Rank (%Roil. rand)	0.71	0.80	1.19	1.28	1.42	1.68	1.78	2.08	1.15	1.08	1.10	1.04	0.98	1.03	0.75	0.66	0.67	0.60	0.97	0.64
Maceral Analyses (% composition - mmf basis)																				
Vitrinite	78.9	79.4	89.1	91.6	83.6	92.2	82.5	86.8	94.4	71.4	93.2	72.6	25.9	70.5	75.5	39.7	60.8	28.0	11.9	23.2
React. S. Fusinite	5.6	6.1	4.0	3.7	6.0	3.3	10.2	8.7	0.8	1.2	1.8	1.6	12.2	10.0	5.3	12.6	7.2	29.0	7.0	23.0
Inert S. Fusinite	2.3	4.0	3.7	2.3	3.4	1.3	3.2	2.1	0.8	0.8	1.2	1.2	50.4	13.1	5.1	19.7	11.2	28.0	51.1	21.9
Fusinite	6.9	4.0	3.2	2.2	6.8	2.5	4.1	2.4	0.4	1.4	1.2	1.2	5.9	2.5	5.8	18.8	12.2	10.0	27.4	27.3
Exinite	6.3	6.5	0.0	0.2	0.0	0.7	0.0	0.0	3.6	25.2	2.6	23.4	5.6	3.9	8.3	9.2	8.6	5.0	2.6	5.5
Maceral Associations (% composition - mmf basis)																				
Liptite	0.8	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2	0.0	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vitrite	72.0	73.6	84.4	87.6	81.8	89.0	81.2	84.6	93.2	39.8	92.4	34.0	13.6	66.0	67.0	22.0	51.0	25.0	14.0	25.0
Clarite	4.2	3.8	0.2	0.4	0.2	0.8	0.2	0.0	1.2	56.0	1.4	59.6	2.6	2.0	14.0	20.0	12.0	9.0	1.0	3.0
Trimacerite	8.4	8.6	0.4	0.4	0.8	0.8	0.6	0.4	3.6	1.0	3.2	1.4	26.6	16.8	7.0	28.0	5.0	7.0	4.0	7.0
Vitrinertite	8.2	6.4	7.8	5.8	10.8	4.8	10.4	10.5	1.2	1.0	0.8	2.4	6.0	8.6	6.0	12.0	11.0	14.0	23.0	13.0
Durite	3.6	2.8	0.2	0.2	0.0	0.4	0.0	0.0	0.0	0.8	0.0	0.8	4.4	3.6	1.0	8.0	6.0	9.0	12.0	8.0
Inertite	2.8	3.8	7.0	5.6	6.4	4.2	7.6	4.5	0.8	0.2	2.2	0.4	46.8	3.0	5.0	10.0	15.0	36.0	46.0	44.0
Mean Max Diameter /um	34.6	34.8	35.0	35.9	36.2	38.2	38.2	39.8	38.2	39.1	38.8	39.2	36.4	37.2	41.0	38.9	44.9	38.2	44.9	41.2
Dominant Maceral Ass.	V	V	V	V	V	V	V	V	V	C	V	C	I	V	V	Mixed	V	I	I	I
Char reactivities (as table 6)																				
R / hr-1	0.96	0.83	0.63	0.59	0.48	0.44	0.37	0.36	0.28	0.33	0.25	0.32	0.31	0.59	0.95	1.40	1.31	0.62	0.65	0.70
ks (x10^3) / g cm-2 s-1	9.1	8.2	6.0	4.9	4.1	3.3	2.6	0.5	6.4	8.4	6.6	7.8	3.1	6.3	7.1	5.3	7.6	3.0	3.1	6.3

BITUMINOUS CHAR CHARACTERISTICS AND REACTIVITIES

Analysis	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Proximate (wt% composition - moisture free)																				
Volatile matter	3.2	3.3	3.2	2.9	2.9	2.8	1.9	0.9	2.6	2.1	2.9	2.5	4.2	3.9	2.2	2.5	1.7	2.2	0.7	1.3
Fixed Carbon	88.8	86.2	77.3	82.8	89.3	82.6	91.3	90.0	93.5	94.6	91.2	93.2	84.3	89.5	78.8	79.2	86.5	49.3	67.7	66.1
Ash	8.0	10.5	19.5	14.3	7.8	14.6	6.8	9.1	3.9	3.3	5.9	4.3	11.5	6.6	19.0	18.3	11.8	48.5	31.6	32.6
Char Morphology (% composition - mmf basis)																				
Fragments	3.0	2.8	3.0	3.0	1.2	1.8	2.6	2.4	3.0	7.2	2.8	7.0	2.2	6.2	9.0	9.0	3.0	6.0	2.0	2.0
Cenosphere - Tenui	64.0	66.0	74.0	78.0	77.8	81.4	72.2	75.4	66.6	86.2	61.4	85.0	10.6	59.2	60.0	30.0	43.0	8.0	7.0	7.4
- Crassi	4.0	3.5	1.5	1.0	2.2	0.8	1.2	2.5	4.2	0.2	4.0	0.6	6.4	4.1	1.0	6.5	9.0	7.5	11.1	2.6
Network - Tenui	12.0	12.4	6.6	6.4	5.0	6.3	6.0	4.8	18.6	5.2	21.8	5.8	4.6	17.3	14.0	8.0	20.0	13.0	9.0	18.8
- Crassi	6.0	4.5	3.5	2.0	2.0	2.5	3.0	3.5	6.8	0.6	8.6	1.0	2.0	4.1	3.0	2.5	6.0	6.5	3.9	14.4
Mixed grain - Porous	6.5	6.0	6.0	3.8	6.0	1.5	8.0	5.0	0.2	0.1	1.0	0.1	4.0	3.8	1.5	14.5	6.5	4.2	9.5	2.6
- Dense	2.5	1.8	0.4	1.4	0.2	1.9	1.4	2.4	0.6	0.3	0.2	0.3	20.8	1.0	3.5	4.5	2.5	29.8	11.5	12.0
Solid - Masive	1.5	1.5	4.5	3.4	4.6	3.3	5.1	3.5	0.0	0.0	0.0	0.0	8.0	2.2	6.5	17.5	6.0	2.3	26.4	10.5
- Inertoid	0.5	1.5	0.5	1.0	1.0	0.5	0.5	0.5	0.0	0.2	0.2	0.2	41.4	2.1	1.5	7.5	4.0	22.7	19.6	29.7
Mean Max Diameter /um	35.0	34.9	35.8	36.7	37.4	38.3	38.1	39.2	39.4	39.0	39.5	39.3	36.6	37.9	43.2	35.8	41.6	32.4	44.2	34.5
TSA / m2 g-1	150	130	120	120	100	100	80	70	100	130	100	120	130	150	110	140	130	100	100	120
R / hr-1	0.96	0.83	0.63	0.59	0.48	0.44	0.37	0.36	0.28	0.33	0.25	0.32	0.31	0.59	0.95	1.40	1.31	0.62	0.65	0.70
ks (x10^3) / g cm-2 s-1	9.1	8.2	6.0	4.9	4.1	3.3	2.6	0.5	6.4	8.4	6.6	7.8	3.1	6.3	7.1	5.3	7.6	3.0	3.1	6.3
Dominant Char Types	C/N	C/N	C	C	C	C	C	C	C/N	C	C/N	C	S/D	C/N	C/N	Mixed	C/N	S/D	S/D	S/D
Dominant Maceral Association									V	C	V	C	I	V						

*C = Cenosphere N = Network S = Solid D = Dense

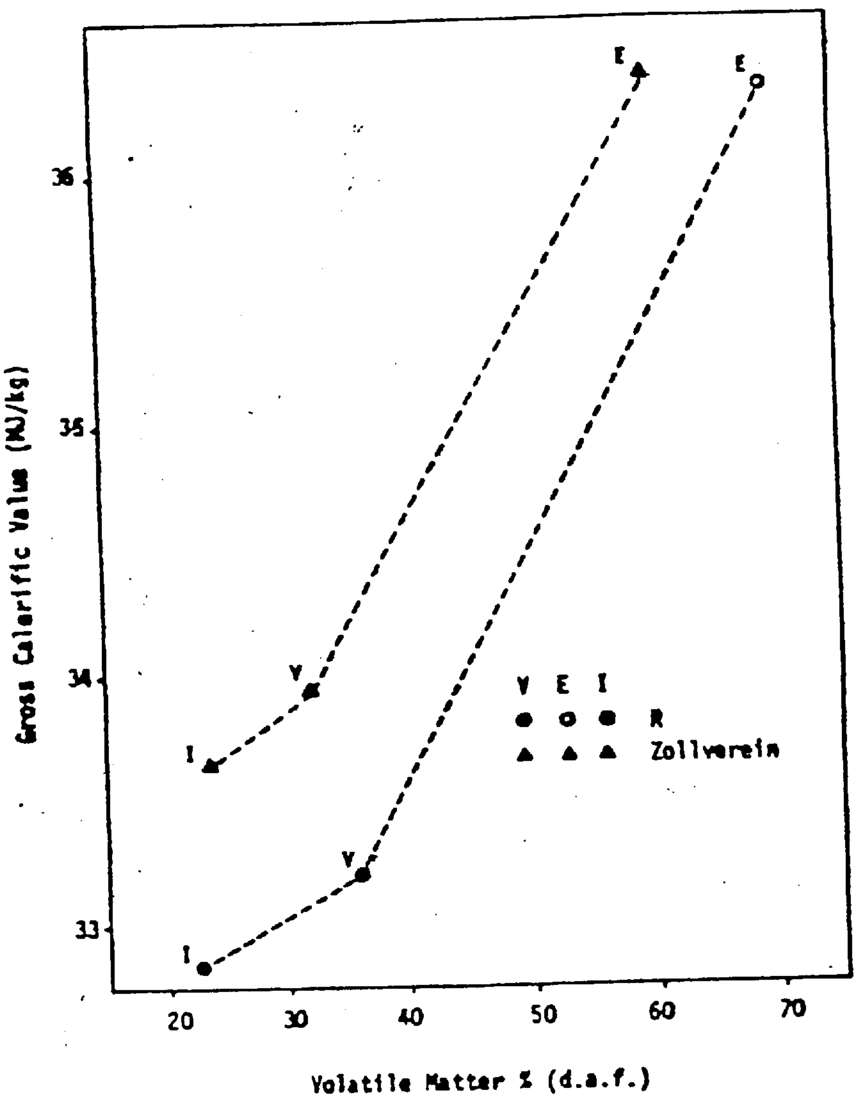


FIG. 1 Heating value and volatile matter content of macerals (*Based on Table 32, p 344,* Stach's textbook of coal petrology, *2nd ed. Gebrüder Borntraeger, 1975*

Table 7 A summary of the major characteristics of the three maceral groups in hard coals (Falcon and Snyman, 1986)

Maceral group/ plant origin	Reflectance: Description	Rank	Reflected light, %	Chemical properties: Characteristic element	Typical products on heating		Combustion properties: Ignition	Burnout
Vitrinite woody trunks branches, stems, stalks, bark, leaf tissue, shoots and detrital organic matter gelified/ vitrinised in acquatic reducing conditions	Dark to medium grey	Low rank to medium rank bituminous	0.5–1.1 1.1–1.6	intermediate hydrogen content	light hydrocarbons	intermediate volatiles decreasing rank	jjj jj j j	jjj jj j j
	Pale grey	High rank bituminous	1.6–2.0	–	–		j	j
	White	anthracite	2.0–10.0	–	–		j	j
Exinite cuticles, spores, resin bodies, algae accumulating in sub-acquatic conditions	Black-brown	Low rank	-0.0–0.5		early methane gas oil	volatile-rich decreasing with rank	jjjj	jjjj
	Dark grey	Bituminous	-0.5–0.9 -0.9–1.1	hydrogen-rich			jjj	jjj
	Pale grey	Medium rank bituminous	-1.1–1.6		condensates wet gases (decreasing)		(j)	(j)
	Pale grey (=vitrinite) to white shadows	High rank bituminous to anthracite	-1.6–10.0					
Inertinite as for vitrinite, but fusinitised in aerobic oxiding conditions	Medium grey	Low rank bituminous	0.7–1.6	hydrogen-poor	–	low volatiles in all ranks	j	j
	Pale grey to white and yellow - white	Medium rank bituminous	-1.6–1.8				j	j
		to anthracite	-1.8–10.0	–	–		(j)	(j)

Capacity or rate: j = slow
jj = medium
jjj = fast
jjjj = very fast

Capacity or rate shown in parenthesis refers to vitrinite.

Relation between reactivities, R & ks and maceral association for Bituminous coals of similar rank